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Distant early-type galaxies: tracers of the galaxy mass assembly evolution

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Abstract. We review the most recent observational results on the formation and evolution of early-type galaxies and their mass assembly by focusing on: the existence, properties and role of distant old, massive, passive systems to $z \sim 2$, the stellar mass function evolution, the "downsizing" scenario, and the high-z precursors of massive early-type galaxies.

Key words. Galaxies: evolution – Galaxies: formation

1. Introduction

Early-type galaxies (ETGs) play a crucial role in cosmology. They represent the most massive galaxies in the local Universe, contain most of the stellar mass ($\mathcal{M}$) and are the primary probes to investigate the cosmic history of galaxy mass assembly. As ETGs are the most clustered galaxies, they are also fundamental in tracing the evolution of the large scale structures. Because of the correlation between the black hole and galaxy bulge masses, ETGs are also important to investigate the co–evolution of normal and active galaxies.

Although ETGs at $z \sim 0$ are rather "simple" and homogeneous systems in terms of morphology, colors, stellar population content and scaling relations (Renzini 2006), their formation and evolution is still a debated question. In the so called "monolithic" collapse scenario (Eggen et al. 1962; Tinsley 1972), ETGs converted most of the gas mass into stars at high redshifts (e.g. $z > 3$) through an intense burst of star formation followed by passive evolution of the stellar population. However, in the modern scenario of CDM cosmology, the evolution of the gravitational perturbations implies that galaxies assembled their mass more gradually through hierarchical merging of CDM halos and make the monolithic collapse unlikely or even unphysical. For instance, the most recent ΛCDM hierarchical models predict that most of the ETG stellar mass is assembled at $0 < z < 1$ (De Lucia et al. 2006). The modern generation of galaxy surveys can test the different predictions on the evolution of the number density, colors, merger types and rates, luminosity and mass functions, and provide a crucial feedback to improve the theoretical simulations.

Despite the intense observational activity on ETG evolution, a general consensus has not been reached yet. For instance, recent results based on optically-selected, moderately deep ($R < 24$) samples of "red sequence" ETGs (e.g. COMBO-17, DEEP2) (Bell et al. 2004; Faber et al. 2005) suggest a strong evolution of the number density with $\phi^*(z)$ displaying an increase by a factor of ~6 from $z \sim 1$

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to $z \sim 0$, and a corresponding increase by a factor of 2 of their stellar mass density since $z \sim 1$. Dissipationless ETG–ETG merging (also called ”dry” merging) is advocated to explain how ETGs assembled at $0 < z < 1$ (Bell et al. 2005; van Dokkum 2005). HST optical, moderately deep ($I < 24$) samples of morphologically–selected ETGs also suggest a substantial decrease of the number density with $n \propto (1 + z)^{-2.5}$ (Ferreras et al. 2005), and spatially resolved color maps show that ∼30-40% of ETGs at $0 < z < 1.2$ display variations in their internal color properties (e.g. blue cores and inverse color gradients) suggestive of recent star formation activity in a fraction of the ETG population (Menanteau et al. 2004). However, the optically-selected ($I < 24$) VIMOS VLT Deep Survey (VVDS) does not confirm the above findings, and shows that the rest-frame B-band luminosity function of ETGs (selected based on the SED) is consistent with passive evolution up to $z \sim 1.1$, while the number of bright ETGs seems to decrease only by ∼40% from $z \sim 0.3$ to $z \sim 1.1$ (Zucca et al. 2005). The overall picture is made more controversial by recent results indicating a weak evolution of the stellar mass function (Fontana et al. 2004; Caputi et al. 2006; Bundy et al. 2006) and that “dry mergers” cannot represent the major contributors to the assembly of ETGs at $0 < z < 1$ (Bundy et al. 2006; Masjedi et al. 2005).

2. The problem of selection effects

After the discovery of the strong clustering of ETGs at $z \sim 1$ (Daddi et al. 2000), it became clear that a major source of uncertainty was the “cosmic variance” (Daddi et al. 2000; Somerville et al. 2004), and that its effects could explain the discrepant results often found by narrow-field surveys, such as the different content of luminous high-z ETGs in the HDF-North and HDF-South (Zepf 1997; Benitez et al. 1999).

Another important source of uncertainty is played by the heterogeneous criteria adopted to select and classify ETGs: deep vs. shallow surveys, optical vs. near-infrared, color vs. morphological vs. spectrophotometric or spectral energy distribution (SED) selections. ETGs have strong k–corrections in the optical as they become rapidly very faint for increasing redshifts and can be easily missed in optically–selected samples (e.g. Maoz 1997), while the k–corrections are much smaller in the near-infrared. A possible example is given by recent results (Yamada et al. 2005) based on a large sample of ETGs at $z \sim 1$ extracted from a ~ 1 square degree field in the Subaru/XMM-Newton Deep Survey . Despite the field as large as that covered in COMBO-17, the number density of ETGs at $z \sim 1$ turns out to be substantially larger than that derived at $z = 0.95$ in COMBO-17, probably due to the deeper and redder–band selection ($z' < 25$ vs. $R < 24$).

Also the “progenitor bias” (van Dokkum & Franx 2001) plays a role in the comparison between low and high redshift ETG samples. As the the morphology of galaxies are expected to evolve, some low-z ETGs were spiral galaxies or mergers at higher redshift. These young ETGs are included in low redshift samples, but drop out of the samples at high redshift. Therefore, the high redshift samples are a biased subset of the low redshift samples, containing only the oldest progenitors of low-z ETGs, i.e. the ones with morphological and spectral properties similar to the nearby ETGs.

3. High redshift ETGs

What is the highest redshift at which we still find ETGs similar to those observed at $z \sim 0$? After the isolated case of a spectroscopically identified old ETG counterpart of a radio source at $z = 1.55$ (Dunlop et al. 1996), studies based on the HDF-South and HDF-North suggested the existence of a substantial number of photometric/morphological ETG candidates up to $z \sim 2$ (Treu et al. 1998; Benitez et al. 1999; Stanford et al. 2004). It was with the recent spectroscopic surveys of near-infrared galaxy samples like the K20 (Cimatti et al. 2002b; Mignoli et al. 2005), GDDS (Abraham et al. 2004), TESIS (Saracco et al. 2003), GRAPES (Daddi et al. 2005a), LCIRS

(Doherty et al. 2005), that high-z ETGs were unveiled up to $z \sim 2$.

The distant ETGs spectroscopically identified at $1 < z < 2$ are very red ($R - K_s > 5$, $I - H > 3$ in Vega photometric system), show the spectral features of passively evolving old stars with ages of 1-4 Gyr (Fig.1), and have large stellar masses with $\mathcal{M} > 10^{11} M_\odot$ (Cimatti et al. 2002a; Cimatti et al. 2003; Cimatti et al. 2004; McCarthy et al. 2004; Saracco et al. 2003; Saracco et al. 2005; Daddi et al. 2005a; Yan L. et al. 2004; Fu et al. 2005). Their spectral properties ETGs suggest a weak evolution in the range of $0 < z < 1$ (Mignoli et al. 2005) (Fig.2). The deepest optical images of ETGs at $0.5 < z < 1.3$ in the Hubble Ultra Deep Field coupled with the GRAPES ACS slitless spectra show that their stellar populations are rather homogeneous in age and metallicity and formed at redshifts $z_f \sim 2 - 5$, and that the isophotal structure of $z \sim 1$ ETGs obeys the correlations already observed among nearby elliptical galaxies, implying no significant structural differences between $z \sim 0$ and $z \sim 1$ (Pasquali et al. 2006). Distant ETGs are also strongly clustered, with a comoving $r_0 \sim 10$ Mpc at $z \sim 1$ measured for the Extremely Red Object (ERO) population (Daddi et al. 2002; Firth et al. 2002; Roche et al. 2003; Brown et al. 2004; Georgakakis et al. 2005), and similar to that of present-day luminous ETGs.

The stellar masses of these galaxies are estimated by fitting their multi–band photometric SEDs with stellar population synthesis models (Fontana et al. 2004; Saracco et al. 2005; Longhetti et al. 2005; Bundy et al. 2006). Such "photometric" stellar masses are in reasonable agreement with the dynamical masses estimated from the absorption line velocity dispersion (di Serego Alighieri et al. 2005; Rettura et al. 2006). ETGs dominate the high-luminosity and high-mass tails of the total luminosity and stellar mass functions up to $z \sim 1$ (Pozzetti et al. 2003; Fontana et al. 2004; Glazebrook et al. 2004; Bundy et al. 2006).

However, due to the strong cosmic variance, the number density of high-z ETGs is still so poorly constrained that the current data at $1 < z < 2$ are consistent with a range from 10% to 100% of the local density of luminous ETGs (Cimatti et al. 2004; Daddi et al. 2005a; Saracco et al. 2005). Old, passive, massive ETGs may exist even at $z > 2$ (Labbe' et al. 2005), but their fluxes are typically beyond the current spectroscopic limits.

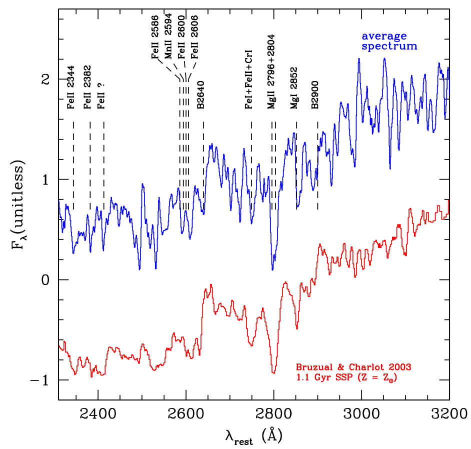

Fig. 1. The observed average spectrum (top) of four massive ETGs at $1.6 < z < 2$ compared with a synthetic spectrum of a simple stellar population (bottom) (Cimatti et al. 2004).

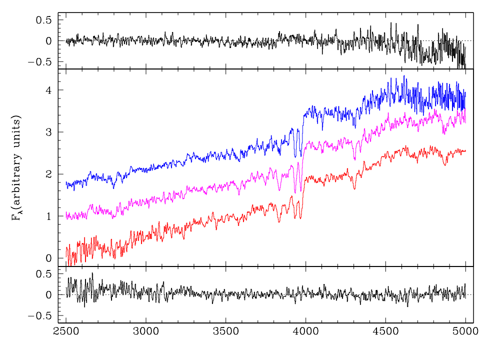

Fig. 2. Composite spectra of the K20 survey ETGs divided in three redshift bins (arbitrary flux scale) (Mignoli et al. 2005). From bottom to top: $0 < z < 0.6$, $0.6 < z < 0.75$, $0.75 < z < 1.25$. The upper and lower panels also show the difference spectra between the intermediate-redshift composite and the high-z and low-z composite spectra respectively.

4. Downsizing

Distant ETGs have a higher stellar mass-to-optical light ratio ($\mathcal{M}/L_R$) than late-type star-forming galaxies at the same redshift (Fontana et al. 2004) (Fig.3). Moreover, the $\mathcal{M}/L_R$ shows an overall trend decreasing from low to high redshifts, but with a substantial scatter that can be interpreted as due to a wide range of formation redshifts and/or star formation histories (see also McCarthy et al. 2001; Cimatti et al. 2003). The typical $\mathcal{M}/L_R$ of more luminous objects ($M_R < -22$) is significantly larger than that of the fainter ones ($M_R > -22$) at low and intermediate redshifts (Fig.3). This implies that, while the $\mathcal{M}/L_R$ of the luminous population is consistent with either very short star-formation time-scales (τ) or high formation redshifts ($z_f \geq 3$) (and some objects appear to require both), the less luminous population experienced a more recent history of assembly, as indicated by the larger τ and lower z_f required to reproduce the typical $\mathcal{M}/L_R$ (Fig. 3). Thus, the most luminous and massive ETGs reach the completion of star formation first, while less massive ones have a more prolonged star formation activity till later times. This *downsizing* scenario was first noted by (Cowie et al. 1996), and it is now supported by several results which suggest that galaxy evolution is strongly driven by the galaxy mass. It is interesting to note that recent studies of ETGs at $z \sim 0$ have reached consistent conclusions (Thomas et al. 2005).

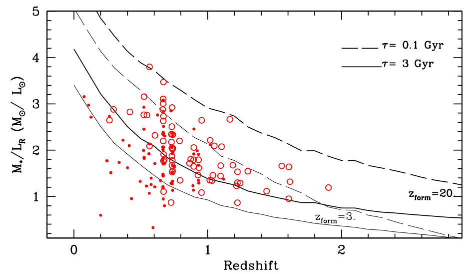

Fig. 3. M_{stars}/L_R ratio as a function of redshift for the spectroscopically identified ETGs in the the K20 sample. Large hollow and small filled circles indicate $M_R < -22$ and $M_R > -22$ respectively. Lines show M_{stars}/L_R values predicted for a set of exponentially–decaying star formation rate models with $z_f = 3$ (thin lines) or $z_f = 20$ (thick lines) and time-scales of $\tau = 0.1$ Gyr (dashed lines) and $\tau = 3$ Gyr (solid lines) (Salpeter IMF and no dust extinction) (Fontana et al. 2004).

Additional clues on downsizing come from the most recent results on the evolution of the Fundamental Plane (FP) both in the field and in distant clusters (van der Wel et al. 2004; Treu et al. 2005; di Serego Alighieri et al. 2005; Jorgensen et al. 2006). The FP at $z \sim 1$ shows already a remarkable small scatter and, with respect to the local FP, an offset and a possible rotation. The evolution of the overall FP can be represented by a mean change in the effective mass-to-light ratio, but with a rate depending on the dynamical mass, being slower for larger masses. This differential evolution is consistent with stellar populations that formed at $z_f > 2$ and $z_f \sim 1$ for high- and low-mass ETGs respectively. Although, the relation between the measured M/L evolution and mass is partially due to selection effects because the galaxies are selected by luminosity, not mass, the M/L – mass relation still holds even if this selection effect is taken into account. These results indicate that the fraction of stellar mass formed at recent times ranges from <1% for $M > 10^{11.5} M_\odot$ to 20%-40% below $M \sim 10^{11} M_\odot$, and that there is no significant difference between the evolution of massive field and cluster ETGs (Fig.4).

Recently it has been found that while the bright end of the cluster colour-magnitude relation is already built at $z \sim 0.8$, the faint end is still in the process of build-up (Tanaka et al. 2005) (see also De Lucia et al. 2004). In contrast to this, the bright end of the field colour-magnitude relation has been built all the way down to the present-day, but the build-up at the faint end has not started yet. This suggests again the downsizing evolutionary pattern: massive galaxies complete their star formation first and the truncation of star formation is propagated to smaller objects as time progresses. This trend is likely to depend on environment since the build-up of the colour-magnitude relation is delayed in lower density environments. The evolution of galax-

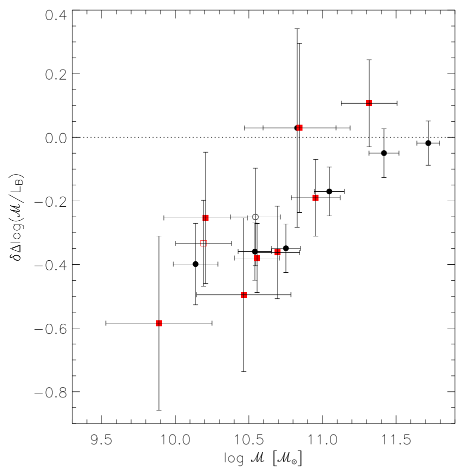

Fig. 4. The differential evolution of the $\mathcal{M}/L_B$ ratio with respect to that of old cluster massive galaxies at the same redshift for ETGs at $z \sim 1$ from the K20 survey (di Serego Alighieri et al. 2005).

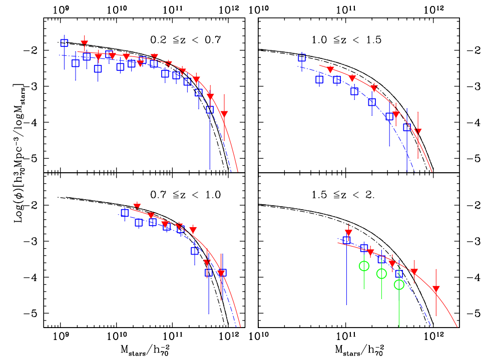

Fig. 5. Stellar mass functions in the K20 sample. Different symbols correspond to different methods adopted to estimate the stellar mass (Fontana et al. 2004). In the highest redshift bin, large hollow circles correspond to objects with only spectroscopic redshift. The thick solid line is the local galaxy mass function (Cole et al. 2001).

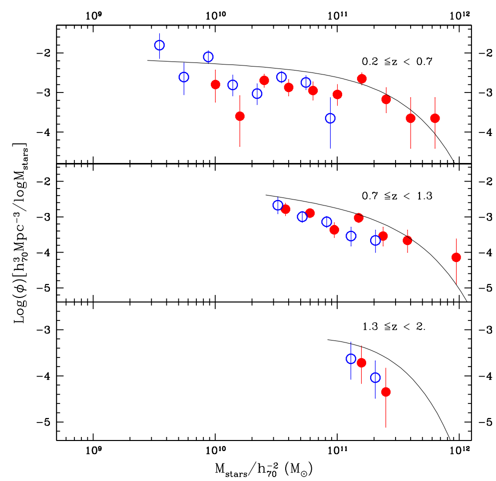

Fig. 6. Stellar mass functions in the K20 sample for different spectral types. Empty points correspond to late spectral types, filled to ETG spectral types. The solid lines show the Schechter fits to the total mass function of the K20 sample at the corresponding redshifts (Fontana et al. 2004).

ies took place earliest in massive galaxies and in high-density regions, and it is delayed in less massive galaxies and in lower density regions.

Other evidences of the downsizing scenario come from the evolution of the stellar mass function (Fig.5-6). Several surveys consistently indicate that the high-mass tail of the stellar mass function (which is populated mostly by ETGs; Fig.6) evolves weakly from $z \sim 0.8-1.0$ to $z \sim 0$ compared to the local stellar mass function and slower than the low-mass tail (Fontana et al. 2004; Drory et al. 2005; Caputi et al. 2006; Bundy et al. 2006; Pannella et al. 2006; Franceschini et al. 2006).

Recently, Bundy et al. (2006) confirmed this downsizing evolution of the stellar mass function per galaxy type up to $z \sim 1$ by using the DEEP2 spectroscopic sample. In addition, they identified a mass limit, $\mathcal{M}_Q$, above which star formation appears to be "quenched". This threshold mass evolves as $\propto (1+z)^{4.5}$, i.e. it decreases with time by a factor of 5 across the redshift range of $0.4 < z < 1.4$, while no significant correlation has been found between downsizing and environment, with the exception of the most extreme environments (i.e. the ones hosting higher numbers of ETGs), where the downsizing seems to be accelerated. Also the spectral properties of ETGs support a downsizing scenario: Fig.7 shows that, at fixed redshift, the D4000 continuum break of ETGs (taken as an age indicator of the stellar popu-

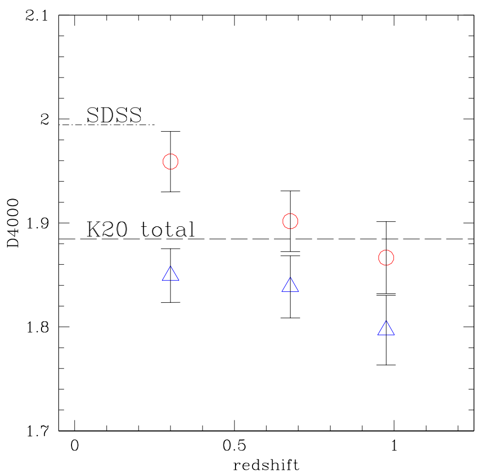

Fig. 7. The 4000 Å break (D4000) in K20 ETG composite spectra (Mignoli et al. 2005). The ETGs in each redshift bin have been divided in two equally populated groups, according to their luminosity. Circles and triangles indicate the brighter and fainter subsamples respectively. The dashed line indicates the D4000 value measured in the average spectrum of all ETGs, whereas the dashed-dotted line is the D4000 measured in the SDSS composite of ETGs (Eisenstein et al. 2003).

lation) is stronger in more luminous systems, suggesting a higher formation redshift of the most massive ETGs (Mignoli et al. 2005).

Additional evidence supporting the downsizing scenario comes from the results on the star formation history properties. Feulner et al. (2005) found that, at all redshifts, lower mass galaxies show higher specific star formation rates (SSFR = $SFR/\mathcal{M}$) than higher mass galaxies, and that the highest mass galaxies contain the oldest stellar populations at all redshifts. With increasing redshift, the SSFR for massive galaxies increases by a factor of 10, reaching the era of their formation at $z \sim 2$ and beyond. These findings can be interpreted as evidence for an early epoch of star formation in the most massive galaxies and for ongoing star formation activity in lower mass galaxies. Similar results have been found also in other recent works (Juneau et al. 2005; Perez-Gonzalez et al. 2005).

5. Comparison with model predictions

These high-z old and massive ETGs are very rare objects in most N-body + semi-analytic simulations published to date. The predicted number densities are much lower than the observed ones (up to a factor of 10 in some cases), with this discrepancy becoming larger for increasing redshift (Somerville et al. 2004). However, as there are enough dark matter halos to host these unexpected massive galaxies (Fontana et al. 2004), what becomes crucial is to understand how the physics and evolution of baryons within the halos can explain the properties of high-z ETGs, and how it is possible to build-up massive ETGs at higher redshifts than expected.

The models incorporating a new treatment of the feedback processes (including AGN), or the ones based on hydrodynamic simulations, seem to obtain a better agreement with the observations (Granato et al. 2004; Menci et al. 2004; Nagamine et al. 2005; Silva et al. 2005). The most recent simulations (Springel et al. 2005) are also capable to predict a downsizing evolutionary pattern for the star formation, but most of the mass assembly still occurs at moderately low redshifts ($0 < z < 1$), and a specific comparison with the observed properties and evolution of the ETGs has not been published yet (De Lucia et al. 2006; Bower et al. 2005). It is interesting to mention that very recent hydrodynamic simulations showed that it is possible to build a realistic massive ($\mathcal{M} \sim 10^{11}$ $M_\odot$) giant elliptical galaxy with a plausible formation history without requiring neither recent major mergers nor feedback from supernovae or AGN, but simply starting from appropriate ΛCDM initial conditions (Naab et al. 2005).

6. Searching for the progenitors

The spectral and color properties of the distant, old ETGs discussed in Section 3 imply unambiguously a star formation history with: strong ($>$ 100 $M_\odot$ yr^{-1}) and short-lived (τ ~0.1-0.3 Gyr) starburst (where

SFR$\propto$ $exp(t/\tau)$), the onset of star formation occurring at high redshift ($z_f > 2-3$), and a passive–like evolution after the major starburst (Cimatti et al. 2004; Daddi et al. 2005a; McCarthy et al. 2004; Longhetti et al. 2005). In addition, the ETG precursors should also have the strong clustering expected in the ΛCDM models for the populations located in massive dark matter halos and strongly biased environments. Recent observations have indeed uncovered galaxies matching the above requirements.

6.1. *BzK*–selected galaxies

The K20 survey unveiled a population of star-forming galaxies at $z \sim 2$ which have strong star formation rates of $\sim 200-300$ $M_\odot$ yr^{-1}, substantial dust extinction with $E(B-V) \sim 0.3-0.6$, stellar masses up to 10^{11} $M_\odot$, merging-like rest-frame UV morphology becoming more compact in the rest-frame optical, strong clustering with r_0 ~8–12 Mpc depending on the adopted redshift distribution, and possibly high metallicity (Daddi et al. 2004a; Daddi et al. 2004b; Daddi et al. 2005b; de Mello et al. 2004; Kong et al. 2005). These starburst galaxies can be efficiently selected at $1.4 < z < 2.5$ with a "reddening-free" color–color diagram (z-K_s vs. B–z; the *BzK* selection) (Daddi et al. 2004b). The *BzK*–selected starbursts with $K_s < 20$ are on average more reddened, massive and star-forming than the optically-selected star-forming galaxies, but they show a significant overlap with other star-forming galaxy populations in the same redshift range selected based on other optical/near-IR criteria (Reddy et al. 2005) or on mid–infrared - to - radio selections (Daddi et al. 2005b; Dannerbauer et al. 2006). The properties of the *BzK*–selected starbursts suggest that these galaxies are massive galaxies caught during their major activity of mass assembly and star-formation, possibly being the progenitors of the present-day massive and metal-rich ETGs. At the stellar mass threshold of $\mathcal{M} > 10^{11} M_\odot$, the number density of these *BzK*–selected starbursts is comparable with that of old passively evolving galaxies in the same redshift range of $1.4 < z < 2.5$ (Daddi et al. 2005b; McCarthy et al. 2004; Kong et al. 2005).

6.2. Other precursor candidates

Other massive galaxy progenitor candidates at $z > 2$ characterized by old stellar populations and/or strong star formation, large stellar and/or dynamical masses and high metallicity include the submm/mm-selected galaxies (Chapman et al. 2005; Dannerbauer et al. 2004; Swinbank et al. 2004; Greve et al. 2005), the "Distant Red Galaxies" selected with $J - K_s > 2.3$ (Franx et al. 2003; van Dokkum et al. 2004; Papovich et al. 2006), the optically-selected BM/BX/LBG systems with bright *K*-band fluxes (Adelberger et al. 2005; Reddy et al. 2005; Shapley et al. 2004), the IRAC Extremely Red Objects (IEROs) (Yan H. et al. 2004), the HyperEROs (Totani et al. 2001; Saracco et al. 2004), and a fraction of dusty EROs (Yan et al. 2005).

6.3. The GMASS project

GMASS (*"Galaxy Mass Assembly ultra-deep Spectroscopic Survey"*) is a new ongoing spectroscopic project based on an ESO Large Program (PI A. Cimatti) aimed at doing ultradeep spectroscopy with VLT+FORS2 of galaxies selected at 4.5μm with Spitzer+IRAC adopting two simple criteria: $m(4.5\mu\text{m}) < 23.0$ (AB) and $z_{phot} > 1.4$. The integration times are very deep (15-30 hours per spectroscopic mask). The main scientific driver of *GMASS* is the spectroscopic identification and study of the high-z progenitors of the massive ETGs in a way complementary to other surveys and with a selection more sensitive to the rest-frame near-IR emission (i.e. stellar mass) up to $z \sim 3$.

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